Effect of Sludge Water from Ready-mixed Concrete Plant on Properties and Durability of Concrete

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Abstract

Besides the increasing disposal cost, sludge water, a wastewater washout from ready-mixed concrete plant, has caused environmental impact problems. This paper investigates the utilization and recycling of sludge water as mixing water for concrete production. The basic properties of sludge water were obtained according to ASTM standard. The properties of dry sludge powder such as chemical compositions and physical properties were investigated. The properties of fresh concrete studied were unit weight, slump, and temperature rise. The mechanical properties of concrete such as compressive strength and modulus of elasticity were studied. The durability aspects such as drying shrinkage and weight loss due to acid attacks were investigated. For parametric study, sludge water was used as a replacement of tap water varied from 0% to 100% by weight. The water-to-cement ratios were 0.5, 0.6, and 0.7. In this study the sludge water tested has a high alkalinity and the total solids content exceeding the limit of ASTM C94 standard, contributing to the more porous and weaker matrix. As a result, when increasing the percentage of sludge water in mixing water, the drying shrinkage and weight loss due to acid attacks increased, whereas the slump and strengths decreased. However, the unit weight and temperature of fresh concrete were not affected by the use of sludge water.

1. Introduction

Along with the increasing demand for ready-mixed concrete in the construction industry, also came together is sludge water (SW), a wastewater discharged from concrete mixing plants and agitator trucks. In general the procedure for disposing of sludge water in the ready-mixed concrete plants consists of two types of sedimentation ponds. The first pond receives excess concretes and wash water from agitator trucks. Subsequently the sludge water and smaller sediments such as sand and cement materials are transferred to the second pond. After settling for a period of time, water from both ponds is recycled for cleaning agitator trucks. Excess concretes in the first pond, and muddy sludge in the second pond then are removed, and disposed of in the landfills. The disposal process is considerably expensive and also causes environmental problems due to the waste materials and high alkalinity in sludge water [1].

Instead of being disposed of, sludge water that meets the requirement of ASTM C94 specification [2] can be recycled and used as mixing water for concrete production without any significant effects on mechanical properties of concrete [1,3,4]. The fine-filler effects and actual water/cement ratio reduction due to fine solids contents in sludge water leads to the reduction of concrete capillary water absorption and porosity possibly improve the durability of concrete [5]. Concrete mixed with sludge water containing residual cement tends to give a shorter setting time and a lower

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flowability [4]. Concerning the above situation, the effective use of the recycling sludge water in concrete production would be of great benefits both in disposal cost reduction and environmental conservation [6].

There has been limited investigation carried out on the recycling of sludge water that does not meet the ASTM C94 specification [2] as concrete mixing water, and particularly on the durability of concrete containing sludge water. Therefore, the aim of this paper was to investigate the effect of sludge water on mechanical properties and durability of concrete including drying shrinkage and weight loss due to sulfuric and hydrochloric acid attacks. The quality and properties of sludge water obtained from a ready-mixed concrete plant in Thailand were analyzed and compared with the ASTM C94 specification [2]. The tests for concrete properties were performed according to ASTM standards [7-14].

2. Experimental Program

In this study, the sludge water was used as a replacement of tap water of 0%, 10%, 20%, 30%, 40%, 60%, 80%, and 100% by weight. The water-to-cement ratios (w/c) were 0.5, 0.6, and 0.7. The ratio of volume of paste to volume of compacted aggregates in dry state (γ) was 1.2. The properties of fresh concrete including initial slump, unit weight, and temperature rise were studied. The mechanical properties of concrete such as compressive strength, flexural strength, and modulus of elasticity were carried out. The durability of concrete in term of drying shrinkage and weight loss due to sulfuric and hydrochloric acid attacks were investigated.

2.1 Materials

1) Cement: A standard Portland cement Type I.

2) Mixing Water: Tap water and sludge water (SW) obtained from a ready-mixed concrete plant in Thailand were used in this study. The process for preparing the sludge water samples started from transferring the sludge water consisting of both clear sludge water and sediments from the second sedimentation pond to the preparation pond. Then the clear sludge water and sediments with the proportion of 1:1 by weight were transferred to the plastic tank, which was modeled by the scale of 1:10 of the sedimentation pond. After uniformly mixed, the sludge water was ready for concrete specimen production.

3) Aggregates: Coarse aggregate was crushed limestone with the maximum size of 20 mm and the absorption of 0.86%. Fine aggregate was a local river sand with the fineness modulus of 2.53 and the absorption of 1.97%. Their grading meets the ASTM C136 requirements [7].

2.2 Testing Procedures

1) The tests for unit weight of concrete in fresh state were performed according to ASTM Standard C138 [8].

2) The concrete slump tests were performed according to ASTM Standard C143 [9].

3) The temperature rise due to hydration reaction of concrete was monitored until the age of 5 days. The 260 x 300 x 400 mm concrete specimens were cast in polystyrene foam boxes. Prior to cast a concrete specimen, a thermocouple was installed in the middle of each foam box to monitor temperature changes, and the data were collected using the Data Logger. After the specimen was cast, the foam box was kept in a 10 mm-thick wooden box. The box lid was closed and sealed.

4) The compressive strength tests of concrete at the ages of 3, 7, 28, 60, and 90 days were performed in accordance with ASTM Standard C39 [10]. The concrete specimens were cast in 100 x 200 mm cylinders.

5) The modulus of elasticity of concrete at the age of 28 days was performed according to ASTM Standard C469 [11].

6) The flexural strength of concrete at the ages of 3, 7, 28, 60, and 90 days were tested according to ASTM Standard C78 [12]. The concrete specimens were cast in the molds with the dimensions of 100 x 100 x 500 mm.

7) The drying shrinkage were performed in accordance with ASTM Standard C596 [13].

The values of drying shrinkage were measured up to 120 days.

8) The resistance of concrete to acid attack was tested in 5% sulfuric and hydrochloric acid solutions. After being cured in water for 28 days, the concrete specimens were submerged in the acid solutions. The weight loss of concrete were measured up to 120 days.

2.3 Concrete Mix Proportions

Details of the mix proportions of concrete used in this study are presented in Table 1 where OPC(Z) denotes a concrete mixed with tap water only, and Z denotes a water-to-cement (w/c) ratio. For an SWX(Z), SW denotes a concrete that sludge water was used as tap water replacement at the percentage of X by weight, and Z stands for a total water-to-cement (w/c) ratio.

Table 1 Mix proportions of concrete (kg/m^3)

Mixed Symbol	Portland Cement Type I	Water	Sludge Water	River Sand	Crushed Limestone
OPC(0.5)	347	173	0	910	966
OPC(0.6)	309	185	0	910	966
OPC(0.7)	279	195	0	910	966
SW40(0.5)	347	104	69	910	966
SW40(0.6)	309	111	74	910	966
SW40(0.7)	279	117	78	910	966
SW60(0.5)	347	69	104	910	966
SW60(0.6)	309	74	111	910	966
SW60(0.7)	279	78	117	910	966
SW80(0.5)	347	35	139	910	966
SW80(0.6)	309	37	148	910	966
SW80(0.7)	279	39	156	910	966
SW100(0.5)	347	0	173	910	966
SW100(0.6)	309	0	185	910	966
SW100(0.7)	279	0	195	910	966

3. Test Results and Discussion

3.1 Properties of Sludge Water

3.1.1 Chemical Compositions and Physical Properties

Test results of the chemical properties of tap water and sludge water are presented in Table 2. It was found that the sludge water has pH value of 12, which is more than the value of 7 for tap water. This is due to the hydration reaction of Portland cement, which forms the products of calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$). In general, calcium ion (Ca^{2+}) and hydroxide ion (OH^-) are dissolved from calcium hydroxide in water, and increase in alkalinity. The total solids content of sludge water is equal to 63,400 parts per million (ppm), which is greater than the limit of 50,000 ppm as specified by ASTM C94 standard [2]. The amounts of chloride ion (Cl^-) and sulfate ion (SO_4^{2-}) of sludge water and tap water are found to be under the standard limit.

Table 2 Properties of sludge water and tap water according to ASTM C 94 standard [2]

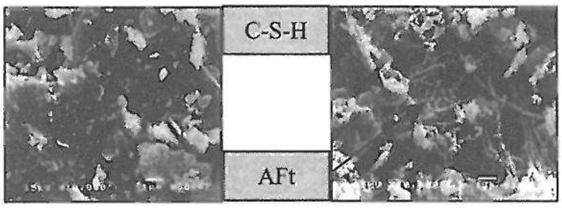
Chemical Properties	ASTM C 94 (ppm)	Tap Water (ppm)	Sludge Water (ppm)
pH	-	7	12
Chloride ion (Cl^-)	≤ 1,000	14.9	25
Sulfate ion (SO_4^{2-})	≤ 3,000	34.96	12.74
Total solids content	≤ 50,000	150	63,400
Specific Gravity	-	1.0	1.02

ppm = part per million

In this study, the dry sludge powder was obtained by drying sludge sediment at temperature of 110 ± 5 °C. The chemical properties of dry sludge powder and Portland cement Type 1 are presented in Table 3. The amounts of chemicals in dry sludge powder including Al_2O_3, Fe_2O_3, MgO, K_2O, Na_2O, SO_3, and Free CaO are similar to those of Portland cement. For the amount of SiO_2 in dry sludge powder (26.87%), which is higher than that of Portland cement (20.84%), this may be caused by leaves decomposed in the sedimentation pond, and also the small sand particles from concrete production. Except for the amount of CaO in dry sludge powder (32%), which is less than that of Portland cement (62%), this is due to the fact that in the sludge water CaO (C as abbreviated), commonly found in major chemical compounds of Portland cement (C_3S, C_2S, C_3A and C_4AF), dissolved from the excess concrete in the washing process resulting in the smaller amount of CaO.

The physical properties of dry sludge powder and Portland cement are presented in Table 3. The LOI content is the loss on ignition of material after burnt at 950 ± 50 °C. The sludge powder has the LOI content of 25.5% compared to 0.96% of Portland cement. The higher LOI content in this case may be caused by the fact that there is not only carbon particles presented, but also leaves and other materials such as calcium hydroxide that can be decomposed at temperature of 950 °C or so. Other condition that could lower the strength of concrete is excess water in sludge powders, in the forms of unhydrated cement, hydrated cement, and hydration products, on the discontinuous structure of C-S-H gel, which is unstable and soluble. The specific gravity and bulk density of sludge powder are found to be less than those of Portland cement. Compared with ASTM C311 standard [14], the strength activity indices at the ages of 7 and 28 day are equal to 64% and 71% respectively, which means the use of dry sludge sediment as a cement replacement of 20% by weight has adverse effect on the compressive strength of mortar. However, when incorporating in concrete, the sludge powders are in the forms of solutions and suspended solids in water, which their actual proportions in concrete are less than the mix proportions shown in Table 1.

The micrograghs at 10,000-time magnification of cement particles and sludge sediments are shown in Fig. 1. It was found that the unhydrated cement particles exist as different angular particles, but the sludge sediments appear in shapes like ettringite (AFt) seen as long slender needles and calcium silicate hydrate (C-S-H) gel as well.



(a) Portland cement type I (x10,000 magnification)
(b) Sludge powder (x10,000 magnification)

Fig. 1 Micrograph of particles at 10,000 – time magnification (a) Portland cement type I and (b) Sludge powder

Table 3 Physical properties of dry sludge powders at temperature 110 ± 5 °C compared with Portland cement Type I

Materials	Chemical Composition (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Free CaO
Portland Cement Type I	20.84	5.22	3.2	66.28	1.24	0.22	0.1	2.41	0.99
Dry Sludge Powder	26.87	6.91	3.17	3.2	1.51	0.98	0.18	3.92	0.62

Physical Properties	Portland Cement Type I	Dry Sludge Powder
1. Loss on Ignition (%)	0.96	25.5
2. Moisture Content (%)	0.19	0
3. Specific Surface Area (Blaine Fineness) (cm^2/g)	3,248	9,940
4. Specific Gravity	3.14	2.5
5. Fineness (% Passing)		
≥ 75 micro-meter	0.5	8.99
75 micro-meter	5.25	9.85
45 micro-meter	3.6	4.94
≤ 36 micro-meter	90.62	76.22
6. Strength Index (compared with the control)		
at the age of 7 days	100	64
at the age of 28 days	100	71

3.2 Properties of Fresh Concrete

3.2.1 Slump

Fig. 2 presents the comparative results of slump tests, where SW X denotes concrete mixed with sludge water as a replacement of tap water at the percentage of X by weight It was found that increasing the percentage of sludge water replacing tap water tends to reduce the concrete slump. This is because the sludge water contains a large amount of sediments in the forms of solids such as unhydrated cement, hydrated cement and fine particles, which tend to increase the amount of water to be adsorbed at the surface and absorbed into the particle, and consequently lower the concrete slump. By increasing the water-to-cement (w/c) ratio, it results in the increase of concrete slump due to the additional amount of free water in concrete.

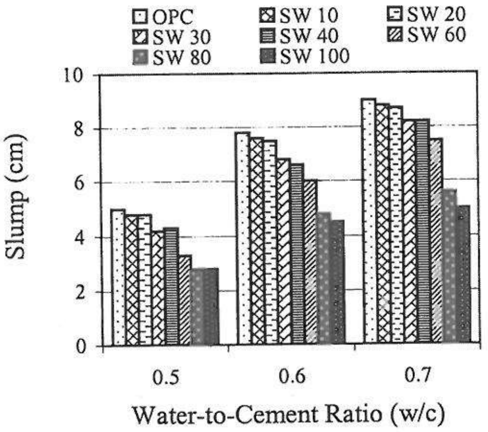


Fig. 2 Slump of fresh concrete

3.2.2 Unit Weight of Fresh Concrete

Fig. 3 shows test results of the unit weight of fresh concrete. The concrete with the higher percentage of sludge water as tap water replacement tends to have the higher unit weight, but does not produce any significant difference compared to the normal concrete (OPC). This is because the specific gravity of sludge water (1.03) is only a little higher than that of tap water (1.00). Overall, when increasing the water-to-cement (w/c) ratio, the unit weight of concrete is reduced due to the increase of the amount of water.

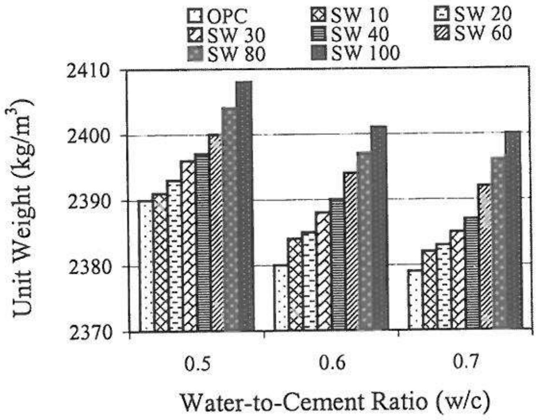
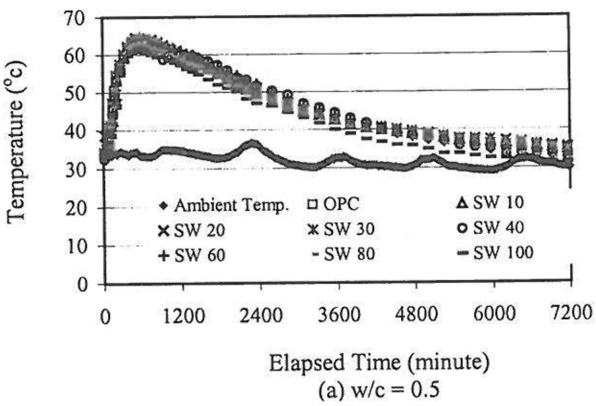


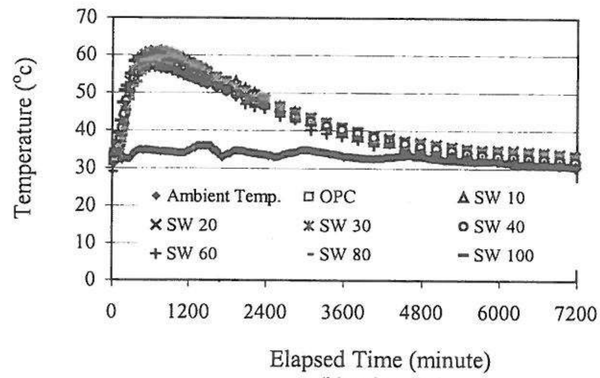
Fig. 3 Unit weight of fresh concrete

3.2.3 Temperature Rise of Concrete

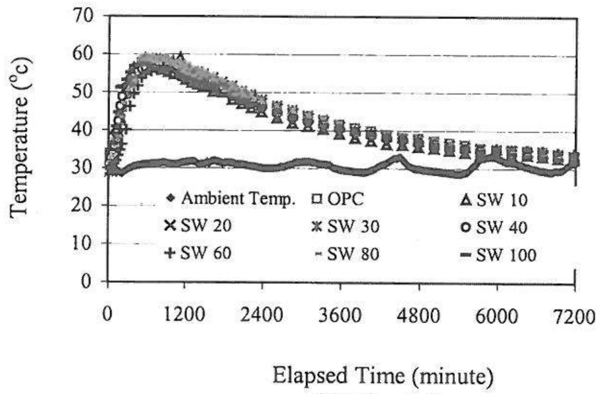
Test results of the temperature rise from room temperature for the concrete mixed with tap water only (OPC) and those mixed with various percentage replacements of sludge water are presented in Fig. 4. Due to the hydration reaction, cement particles react with water and generate the heat causing temperature to rise rapidly to the peak within 12 hours, and then decrease slowly close to room temperature within 5 days. From the results, the concretes mixed with sludge water tend to have a little increment in temperature at the beginning due to a small amount of unhydrated cement particles in sludge water. It shows that the utilization of sludge water in the concrete mixes has no significant effect on the temperature rise due to the hydration reaction. Noticeably, the increase of water-to-cement (w/c) ratio tends to lower the temperature rise of concrete due to the reduction of cement content in the mix.



(a) w/c = 0.5



(b) w/c = 0.6



(c) w/c = 0.7

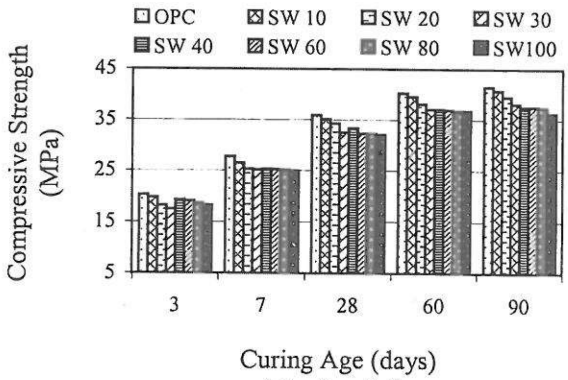
Fig. 4 Temperature of concrete (measured inside the specimens)

3.3 Mechanical Properties of Concrete

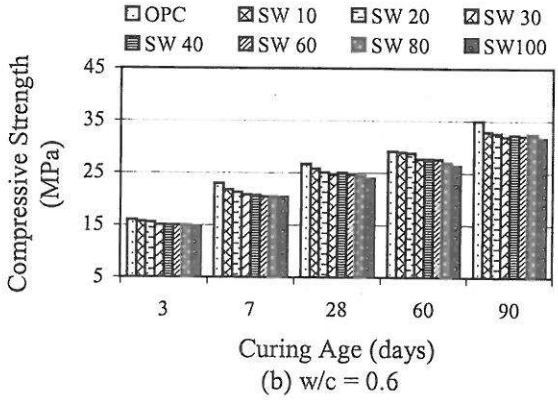
3.3.1 Compressive Strength

Fig. 5 shows test results of the compressive strength of control concrete (OPC) and concretes mixed with sludge water as a replacement of tap water. It was found that increasing the percentage of sludge water tends to reduce the compressive strength of concrete. It is because, during the hydration process, the rod-like ettringite found in sludge water generally transforms to unstable compounds such as mono sulfate aluminates, and finally dissolve. As a result, there are additional pores appeared in the concrete matrix causing the lower strength. Also with the higher alkalinity in the matrix, these conditions contribute to the increase of thickness of the duplex film, a layer within the interfacial transition zone between cement paste and aggregate, resulting in the increase of thickness of the interfacial transition zone itself. Consequently, these phenomena cause the weaker bond between aggregate and cement paste, which yield the lower compressive strength of concrete [15].

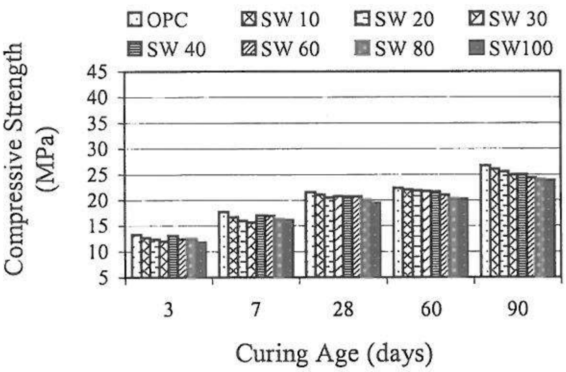
From results in Fig. 5, the concretes mixed with the maximum of 40% by weight of sludge water replacing tap water yielded the compressive strength more than 90% of that of the control concrete which is above the recommended value by ASTM C94 standard [2] for concrete mixing water. Overall the compressive strength of concretes mixed with sludge water is in the range of 85% to 94% of control concrete. For the influence of various water-to-cement ratios (w/c), 0.5, 0.6 and 0.7 respectively, it was found that increasing the water-to-cement ratio (w/c) tends to reduce the compressive strength of concrete. This is because the increase of water-to-cement ratio (w/c) results in the increase of porosity in the concrete matrix, which eventually lowers the density of concrete, contributing to the decrease in the compressive strength of concrete [16].



(a) w/c = 0.5



(b) w/c = 0.6



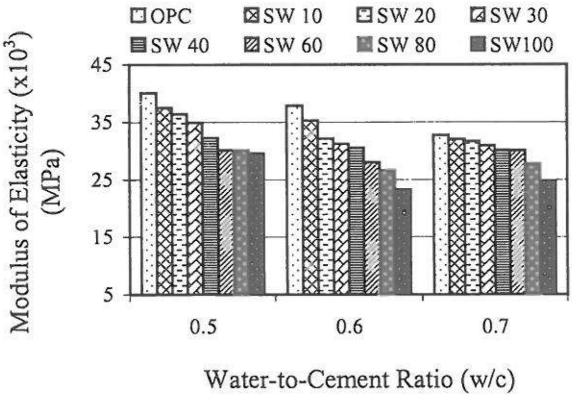
(b) w/c = 0.6

Remark OPC denotes concrete mixed with tap water
SWX denotes concrete mixed with sludge water as a replacement of tap water at the percentage of X by weight

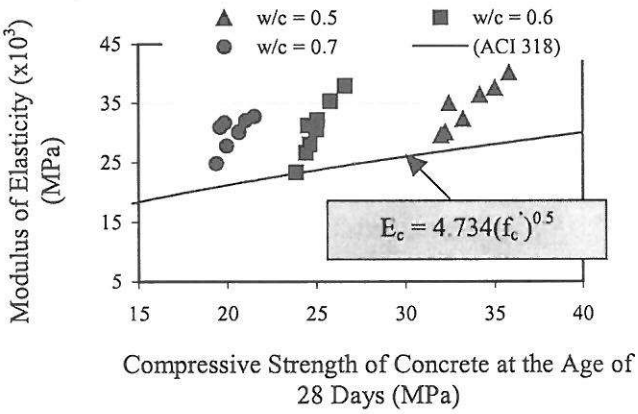
Fig. 5 Compressive strength of concrete

3.3.2 Modulus of Elasticity at the Age of 28 days

Test results of the modulus of elasticity of normal concrete (OPC) and concretes containing sludge water at the age of 28 days are shown in Fig. 6. The results show that the modulus of elasticity of concrete decreases when the proportion of sludge water as a replacement of tap water increases. This is due to the sludge water consisted of unhydrated cement particles, hydrated cement, and fine particles, contributing to the discontinuity between the calcium silicate hydrate (C-S-H) gel and aggregates, which eventually leads to decreasing the modulus of elasticity of concretes. Another contribution to the lower strength is the additional pores from the dissolution of existing ettringite in sludge water. When comparing the values of the modulus of elasticity of concretes tested with the value recommended by the ACI 318 [17], as seen in Fig. 6(b), it was found that the values of the modulus of elasticity of the control concrete (OPC) and the concretes containing sludge water are higher than the value recommended by ACI 318 [17].



(a) Modulus of elasticity

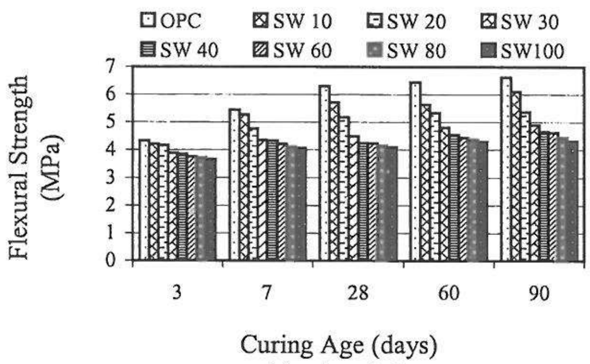


(b) Modulus of elasticity of concrete, of concrete at the age of 28 days together with ACI 318 recommendation [17]

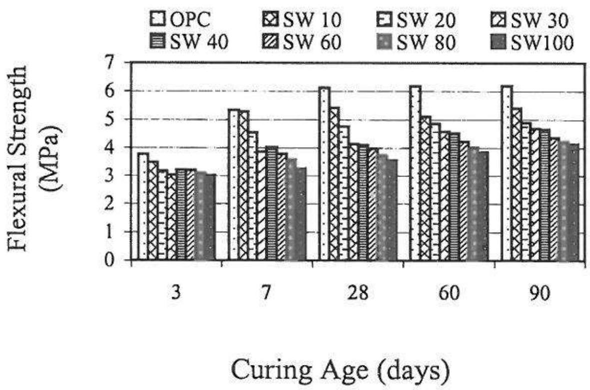
Fig. 6 Modulus of elasticity of concretes at the age of 28 days

3.3.3 Flexural Strength

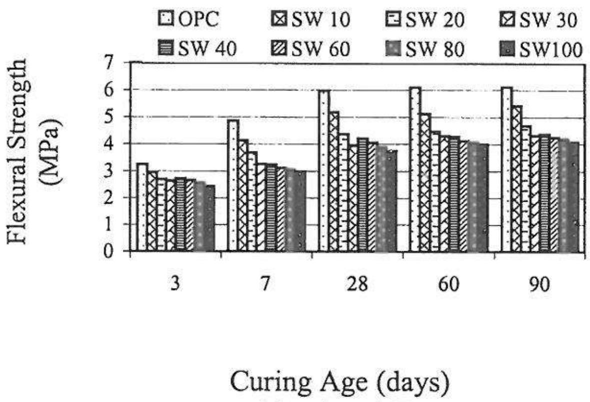
As shown in Fig. 7, overall the rate of flexural strength development is rapid at the beginning, until 28 days of curing it becomes flatten due to the decreasing rate of hydration reaction. It was found that increasing the percentage of sludge water replacing tap water tends to reduce the flexural strength of concretes. Except for concretes with 10% replacement of sludge water, after 7 days of curing, the flexural strength of concretes mixed with sludge water as tap water replacement are noticeably lower than those of the control concretes (OPC). Similar to the results of compressive strength, increasing the water-to-cement ratio (w/c) reduces the flexural strength of concrete. Overall results indicate the same trend as previously described that the bond strength between cement paste and aggregate is weaker when increasing the amount of sludge water as a tap water replacement, and also by the increase of water-to-cement ratio (w/c).



(a) w/c = 0.5



(b) w/c = 0.6



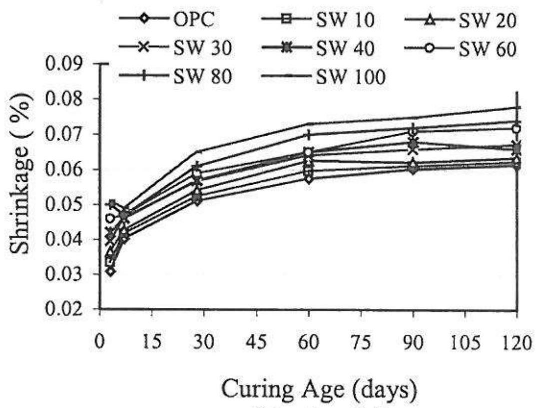
(c) w/c = 0.7

Fig. 7 Flexural Strength of Concrete

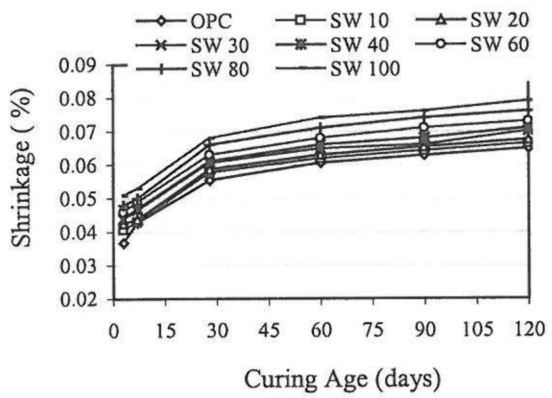
3.4 Durability of Concrete

3.4.1 Drying Shrinkage

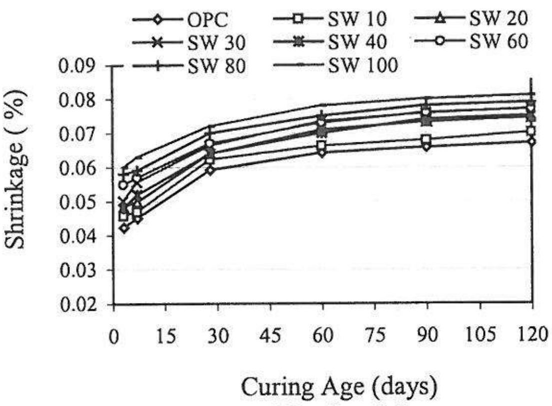
From test results as shown in Fig. 8, it is found that the concretes mixed with sludge water replacing tap water yield the higher drying shrinkage. Increasing the percentage replacement of tap water tends to increase the drying shrinkage. The sludge water due to the dissolution of unstable ettringite yields more capillary pores compared to the normal concrete (OPC). The pore water gradually migrates to the atmosphere causing the more porous matrix and shrinkage. From the results, the drying shrinkage rates are high at the beginning because the concretes were transferred from the 100% relative moisture condition to air drying in the ambient atmosphere (60±5% relative moisture) that the free moisture in the matrix and on the surface dissipates at a faster rate [16]. After a period of time, only moisture in the matrix have migrated to the atmosphere, and some of the capillary pores have shrunk to trap the moisture inside that cause the slower rate of shrinkage. The important controllable factor affecting shrinkage is the amount of water per unit volume of concrete. The higher water-to-cement (w/c) ratio yields the higher drying shrinkage.



(a) w/c = 0.5



(b) w/c = 0.6



(c) w/c = 0.7

Fig. 8 Drying shrinkage of concrete

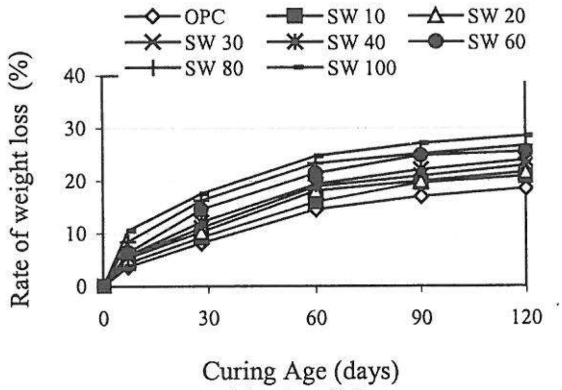
3.4.2 Resistance to Acid Attack

3.4.2.1 Sulfuric Acid Attack

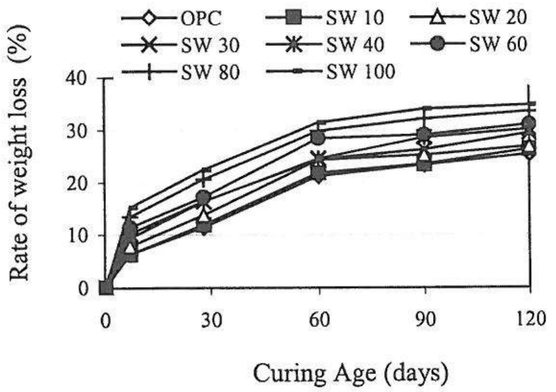
The effect of the addition of sludge water on the sulfuric acid resistance was investigated. Results presented in Fig. 9 show that the sludge water have a negative effect on the acid resistance. The percentage of weight loss due to the acid attack increases when increasing the proportion of sludge water replacing tap water. A faster rate of weight loss was observed at the beginning period and over time the weight loss continues with a slower rate. Equation (1) expresses the acid attack mechanism. The reaction between calcium hydroxide ($Ca(OH)_2$) in the concretes and sulfuric acid (H_2SO_4) yields a low soluble product of calcium sulfate or gypsum ($CaSO_4.H_2O$) as a layer on the surface of concrete, and also with forming by loose bonds the layer is prone to leaching and deterioration.

$$Ca(OH)_2 + H_2SO_4 \text{ --------> } CaSO_4 + 2H_2O \qquad (1)$$

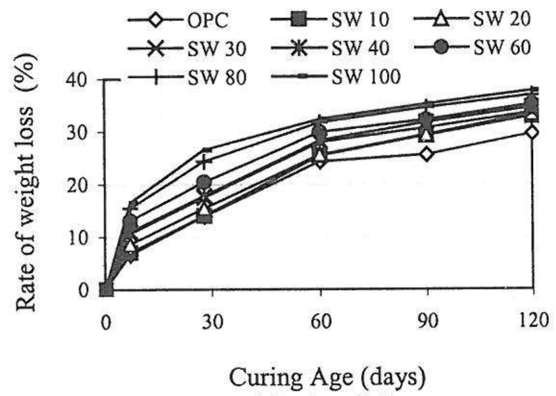
For the concretes mixed with sludge water, another contribution to the higher percentage weight loss compared to the control concrete is the additional calcium hydroxide, in the form of unstable ettringite, causing the concrete matrix to be more porous and susceptible to the acid attack through the capillary pores. From the results, the higher water-to-cement (w/c) ratio adding more water in the matrix also yields the more porous concrete that is prone to more negative effect on the acid attack.



(a) w/c = 0.5



(b) w/c = 0.6



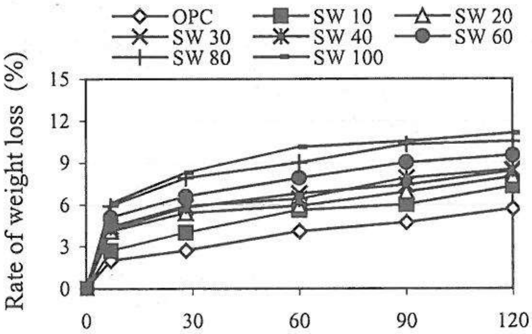
(c) w/c = 0.7

Fig. 9 Weight loss due to sulfuric acid attack

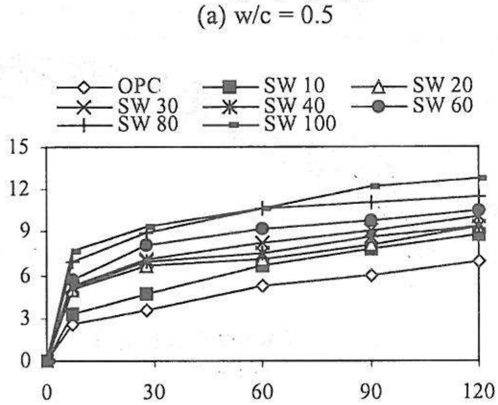
3.4.2.2 Hydrochloric Acid Attack

Results presented in Fig. 10 show that the sludge water have a negative effect on the resistance of hydrochloric acid attack. Increasing the proportion of sludge water replacing tap water yield the higher percentage of weight loss due to the acid attack. A faster rate of weight loss occurred at the beginning and over time the weight loss continues with a slower rate. Equation (2) expresses the acid attack mechanism. The reaction between calcium hydroxide ($Ca(OH)_2$) in the concretes and sulfuric acid (HCl) forms calcium chloride ($CaCl_2$) that is a more soluble product compared to the calcium sulfate from sulfuric acid attack. This makes the concrete more susceptible to leaching and deterioration due to the acid attack when increasing the amount of sludge water. From the results, the higher percentage of sludge water as tap water replacement indicating the additional calcium hydroxide results in the higher percentage of weight loss compared to the control concrete.

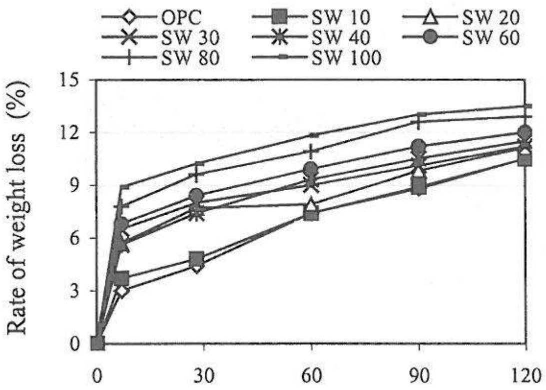
$$Ca(OH)_2 + HCl \dashrightarrow CaCl_2 + 2H_2O \qquad (2)$$



(a) w/c = 0.5



(b) w/c = 0.6



(c) w/c = 0.7

Fig. 10 Weight loss due to hydrochloric acid attack

4. Conclusions

1) Sludge water from the ready-mixed concrete plant has alkalinity as a pH of 12, which is considerably more than that of tap water, and has a total solids content of 63,400 ppm exceeding the value of 50,000 ppm as per ASTM C94 standard [2].

2) The compressive strength, flexural strength and modulus of elasticity of concrete tend to reduce with the increase in proportion of sludge water as a replacement of tap water. Overall the compressive strengths of concretes mixed with sludge water are in the range of 85% to 94% of control concrete, which are comparable to ASTM C94 requirement on mixing water for concrete. When compared with ACI 318 standard [17], the modulus of elasticity of concretes mixed with sludge water is higher than or comparable to the recommended value.

3) The increase of the proportion of sludge water as a replacement of tap water have no effects on the unit weight of fresh concrete and the temperature change of concrete during curing. On the other hand, the slump of concrete containing sludge water tends to be reduced when compared with the control concrete mixed only with tap water.

4) For durability of concrete, due to the increase in soluble products from the reactions between the acids and the additional calcium hydroxide of concretes mixed with sludge water, the increase in proportion of sludge

water as a replacement of tap water yield the negative effects on the drying shrinkage and the resistance to acid attack.

5. Suggestions for the Use of Sludge Water in Concrete Production

1) Due to the variation of properties of sludge water such as total solids content, chloride, sulfate, etc., before using sludge water for concrete production in the field, the basic properties including physical and chemical properties should be investigated periodically. This shall be done for the determination of adjusting the amount of sludge water in the concrete mix.

2) For the utilization of sludge water, with a total solids content of or less than 63,400 ppm, as a partial or total replacement of tap water in concrete production, the test results in accordance with ASTM C94 standard [2] indicate that the compressive strength of concretes containing sludge water are comparable to the concrete mixed with unclean water. The concrete mix proportion containing sludge water shall yield the compressive strength not less than 90% of normal concrete. From the test results, the compressive strengths of concretes containing sludge water are in the range of 85% to 94% of control concrete. It can be concluded that sludge water is applicable to use in concrete production with consideration of the type of structure including compression members such as columns. For the bending structures such as beams, it is not recommended to use concrete mixed with sludge water due to its adverse effect, which considerably reduces the flexural strength of concrete. For mass concrete, such as concrete used in foundation works, it is appropriate to use concrete containing sludge water with no effect on the temperature change of concrete during the curing period.

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